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TITLE: Corneal Damage from Infrared Radiation

PRINCIPAL INVESTIGATOR: Russell L. McCally, Ph.D.

CONTRACTING ORGANIZATION: Johns Hopkins University
Laurel, Maryland 20723-6099

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Russell L. McCally, Ph.D.

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This report summarizes our research during the past year on the interaction of short pulses of infrared radiation produced by a CO_2-TEA laser with the cornea. The report discusses the re-establishment of our laboratory, revision and testing of our computer program for computing temperature histories, confirmation of earlier results for single-pulse damage thresholds, the determination of the damage threshold for a sequence of two 80 ns pulses at 5 Hz, and correcting problems with the laser in order to achieve uniform pulse amplitudes at higher pulse repetition frequencies.

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Russell L. McCalley 11/27/96

PI - Signature Date

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Introduction

The military employs a broad range of laser radiation in training devices, rangefinders, target designators, communications devices and other instruments. This equipment emits either single pulses or sequences of pulses in beams of various diameters. The research performed under this contract directly supports the U. S. Army Medical Research and Materiel Command (USAMRMC) mission to assess the health effects and hazards of nonionizing electromagnetic radiation from such laser systems. The data obtained will support evaluation of current permissible exposure limits and will aid health policy makers, both within and outside the DoD, in developing injury prevention criteria. The general approach is to make direct determinations of damage threshold levels for non-ionizing radiation for specific exposure conditions (e.g., wavelengths, pulse durations, etc.) and to develop models of the damage mechanism that enable the extension of the results to other exposure conditions.

Under past support from the Army Medical Research and Development Command we determined corneal damage thresholds for CO_2 lasers that emit single and sequences of pulses having durations of 1 ms and longer and developed thermal damage models for predicting this type of damage[1-5]. We also determined corneal damage thresholds for single 80 ns pulses of CO_2 laser radiation and for three multiple-pulse (2 pulses at 1 Hz.; and 2 and 8 pulses at 10 Hz.).[6, 7] In the case of these very short pulses, damage mechanisms other than thermal (e.g., acoustical pressure pulses) could also play a role. Light and electron microscopy revealed unusual disruptions of the anterior epithelial surface for the threshold single-pulse exposure. The characteristics of these disruptions differed from those observed with simple thermal damage at longer pulse durations and appeared to be consistent with a mechanical [e.g., acoustic] damage mechanism. However, the calculated temperature increase produced by the threshold exposure was only slightly lower than that calculated for threshold exposures having durations of 1 ms and longer.[6, 7] Thus we could not exclude a thermal damage mechanism, with the sharp temperature gradients leading to marked differences in the character of the damage as compared to damage from longer duration exposures. In the case of the preliminary multiple-pulse data noted above, the 10 Hz results contained an (apparent) discrepancy in that the threshold for the 8 pulse sequence was higher than that for the 2 pulse sequence.

This study aims to expand the database of thresholds for sequences of 80 ns of CO_2 laser pulses and to refine the preliminary 10 Hz. thresholds. In addition it will attempt to clarify the damage mechanism(s) for these types of pulses and ultimately will begin to address damage from mid-infrared wavelengths where the radiation is more penetrating.

Methods

Short-pulse exposures are made with a Boston Laser (Model 220S) CO_2-TEA laser operated in the TEM_{00} mode. This laser delivers 80 ns pulses at pulse

repetition frequencies up to 20 Hz. Mode quality is verified and the beam diameter is measured at the beginning of each experimental session using a Spiricon linear pyroelectric array. The detector has 64 elements on 200 μm centers. It is mounted on a vertical micropositioner and is read out with a LeCroy 9354M digital oscilloscope. These latter two pieces of equipment are major improvements to the apparatus since our previous contract. Figure 1 shows the profile of a beam having a 1/e diameter of 3.50 mm. Pulse energy is measured with a Scientech detector immediately before and immediately after each exposure.

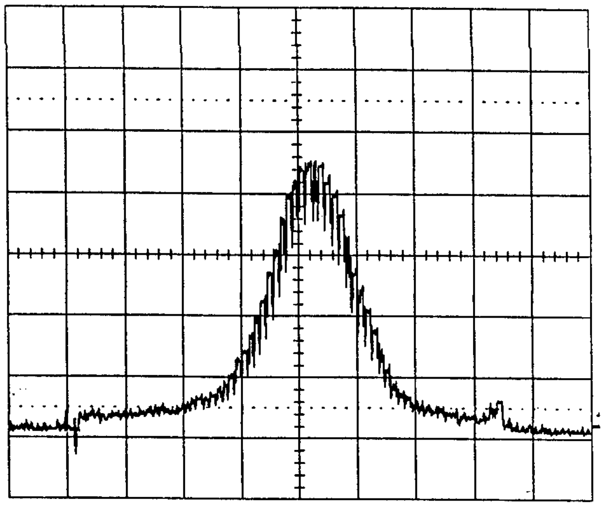

Figure 1: Profile of TEM_{00} beam $d_{1/e}$ = 3.50 mm.

New Zealand white rabbits of either sex weighing 4 - 5 pounds are used for the experiments. The rabbits are treated in accordance with the *Guide for the Care and Use of Laboratory Animals* (DHEW Publication No. (NIH) 85-23, Revised Edition, 1985 and with the Association for Research in Vision and Ophthalmology Resolution on the Use of Animals in Research. Prior to exposure the rabbits are anesthetized with an intramuscular injection of xylazine and ketamine hydrochloride (Rompun-Ketaset) in the proportions: 60% of 20 mg/ml Rompun to 40% of 100 mg/ml Ketaset by volume. In addition a topical anesthesia (tetracaine hydrochloride 1/2%) is applied to each eye before exposure and a drop of homatropine bromide 5% is instilled to dilate the pupil. This facilitates examination of the exposed corneas for minimal lesions. The anesthetized animals are placed in a conventional holder for exposure. A speculum is inserted in the eye about one minute before exposure and the eye irrigated with BSS solution (Alcon Surgical); however, in order to create a reproducible "tear film," the irrigation is stopped 20 sec before the exposure and excess fluid is blotted at the limbus. One exposure is made to each eye. One-half hour after exposure the rabbits, still under anesthesia, are sacrificed with Beuthanasia-D administered in an ear vein. The eyes are enucleated and examined for damage using a Nikon FS-3 photo slit-lamp.

The criterion that we use for minimal epithelial damage is that due to Brownell and Stuck[8], namely the presence of a superficial gray-white spot that develops within one-half hour after exposure. We have found that the damage threshold is sharply defined; i.e., only rarely is there overlap between exposures that produce minimal lesions and those that do not. Therefore we do not use statistical procedures such as probit analysis in order to determine the threshold, as these would require the use of more animals than we deem necessary. We make one exposure per eye, bracketing exposures above and below threshold. The bracket is narrowed until there is only about a 10% difference in energy between

an exposure that produces a minimal lesion and one that does not. The threshold is taken to be at the center of the bracket.

Temperature calculations are based on a Green's function solution to the heat conduction equation for an incident beam with a Gaussian irradiance profile that is absorbed according to Beer's law. The beam is assumed to impinge on a semi-infinite slab and to have a constant peak irradiance for the duration of the exposure. We also assume that conduction is the only mode of heat transfer and that no heat is lost to the air at the epithelial interface. The solution $T(r,z,t)$, where r is the radial distance from the beam axis, z is the depth into the cornea, and t is time, has the form of a definite integral that can be evaluated numerically.[1, 4, 9] We wrote a program to evaluate this integral under our initial contract. The program ran on the APL mainframe computer which is no longer in operation. We have modified the original program as discussed below so that it runs on a desktop computer (in our case a Power Macintosh). The modifications are discussed below and a copy of the new program is listed in Appendix 2.

Results and Discussion

The contract with USAMRMC was signed November 9, 1995. Budgets were established at APL by the middle of December. During January we (Drs. R. L. McCally and C. B. Bargeron) conferred with the Contracting Officer's Representative, Mr. Bruce Stuck, to reaffirm his research needs and priorities. In this regard it should be noted that the Statement of Work for the first year dated February 24, 1995 was the same as in the original 1991 proposal and we wanted to confirm that the research described there was still appropriate. That Statement of Work was as follows:

1. The data base of threshold conditions for 80 ns pulses from CO_2-TEA lasers will be extended by measuring the threshold energy densities for sequences of 32, 128 and 1024 pulses at 10 Hz and sequences of 2, 8, 32 and 128 pulses at 20 Hz. The existing thresholds for 2 and 8 pulses at 10 Hz will be refined.

2. An understanding of the damage mechanism for such pulses will be pursued by:

   a) determining how lowering the temperature of the epithelium affects the threshold,

   b) obtaining light and electron micrographs of the damage,

   c) using high-speed photography to investigate ablation of material from the corneal surface, and

   d) measuring pressure transients in model systems.

3. The required characteristics of potential near-infrared laser source(s) for damage studies will be identified by performing detailed temperature calculations in the 1.3 to 2.5 μm wavelength region.

Mr. Stuck confirmed that the multiple-pulse damage threshold determinations noted there were still of major interest. Because our laboratory had not been used for this type of research since termination of our last contract in 1989 many of the pieces of equipment had migrated to other experiments. Thus we began a major effort to locate them and re-assemble the apparatus so that the threshold determinations could be made.

As noted above in the Methods Section, the program for calculating temperature histories that we had developed during our earlier contract (1977-89) had to be revised because the mainframe computer on which it was designed to run is no longer in operation. The original program used mainframe library routines for calculating complementary error functions and the routine DCADRE for evaluating the integrals that give temperature as a function of time and position in the cornea. The routine DCADRE was an adaptive Gaussian quadrature method for approximating integrals that also was no longer available. In revising the program for the Power Macintosh using FORTRAN 77 (LS FORTRAN, Fortner Research LLC) we used routines obtained from Numerical Recipes[10] for evaluating the complementary error functions and the IMSL routine DQDAG for evaluating the integrals. The routine DQDAG uses a globally adaptive scheme that is based on Gauss-Konrad rules. We checked the accuracy of the error function calculations by comparing the results to values computed using Mathematica (Wolfram Research). The results agreed to double precision accuracy (15 significant figures). The entire program was tested by repeating several calculations done previously on the mainframe. Tests were done for both single- and multiple-pulse exposures, for absorption coefficients corresponding to 10.6 μm and 2.01 μm radiation, and for exposure durations ranging from 1.7 ns to 5 sec. In all cases the results agreed with the previous calculations to the number of decimal figures printed in the original mainframe output (usually 6).

After re-installing the experimental set-up, we first made a few single-pulse exposures to reconfirm our earlier results and to refamilarize ourselves with the experimental protocol. Using a TEM_{00} beam with a 1/e diameter of 3.32 mm we exposed corneas with peak energy densities of 442, 397 and 329 mJ/cm^2. The first two exposures caused superficial lesions and the third exposure did not. In our earlier study[6, 7] we had obtained a threshold of 360 mJ/cm^2; thus, these exposures confirmed that the apparatus and our methodology give results for single pulses that are consistent with those obtained previously.

We set out to refine the threshold for 2 pulses at 10 Hz but encountered difficulty obtaining consistent pulses. The second pulse either had an amplitude that was significantly lower than the first, or was missing altogether. Initial attempts to solve this problem were unsuccessful. A major difficulty was that Boston Laser has been out of business for several years and the documentation for the laser is very sparse (it lacks most circuit and gas flow diagrams). We did find that we were able to obtain consistent pulses up to 5 Hz. Thus we temporarily proceeded with determining the damage threshold for a sequence of 2 pulses at 5 Hz. The result, 275 mJ/ cm^2/pulse, lies between our earlier results for 2 pulses at 1 Hz (300 mJ/ cm^2/pulse) and 2 pulses at 10 Hz (200 mJ/ cm^2/pulse)[6, 7]. This

threshold exposure resulted in a calculated peak temperature increase on the beam axis 10 μm beneath the anterior tear layer of 26.2 C (see Fig. 2).

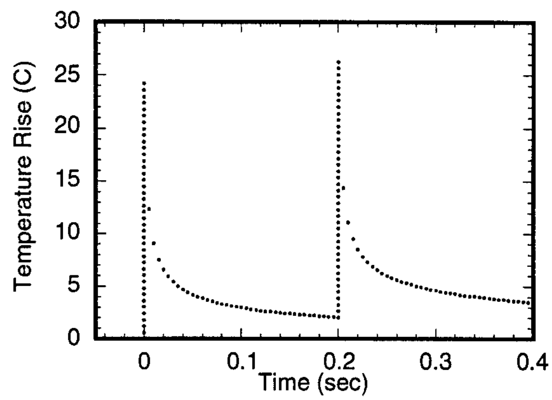

Figure 2: Temperature history for threshold exposure (2 pulses at 5 Hz).

After completing this determination we returned to solving the problem of inconsistent pulsing at frequencies above 5 Hz. We cleaned and refurbished the spark gap and verified that the capacitors were charging and discharging properly. Most of this work was done subsequent to the closing date for this report; however the problem, which we found involved gas flow, <u>is</u> solved. In order to verify operation at 10 Hz we used the Scientech detector to measure the energy of ten single pulses and the integrated energy of ten 2-pulse sequences. We obtained an average value (±S.D.) of 29.90±1.79 mJ for the single pulses and 30.75±1.06 mJ for one-half the integrated energy of the 2-pulse sequences. These values are statistically indistinguishable (t = 0.11). We are now in the process of completing the damage determinations given in the Statement of Work.

Our Contracting Officer's Representative, Mr. Bruce Stuck, and Dr. David Sliney of the United States Army Center for Health Promotion and Preventive Medicine visited APL on July 31 to discuss progress and future plans. We discussed several factors to consider in planning future research. Among these were the importance of gathering data in the 1.3 to 1.5 μm spectral region where the radiation is more penetrating. In this spectral region particularly, and perhaps in the region near 2 μm, it was emphasized that it would be important to consider late effects as well as immediate effects of exposures. As we progress with the threshold determinations we will confer again with Mr. Stuck to formulate the next steps.

Conclusions

The program we developed for calculating temperature histories resulting from exposure to a laser beam having a Gaussian irradiance profile was updated to run on a desktop computer. The revision required new routines for computing complementary error functions and for evaluating the definite integral. The program was tested extensively and it was shown to give results in exact

agreement with the earlier version. We reconfirmed our earlier damage threshold for a single 80 ns pulse and determined the damage threshold for a sequence of two 80 ns pulses at a pulse repetition frequency of 5 Hz. The result was consistent with our earlier determinations of 2 pulses at 1 Hz and 2 pulses at 10 Hz. Problems of achieving uniform pulse amplitudes at 10 Hz were solved.

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Appendix 1

Personnel Paid by Contract DAMD17-96-C-6005:

R. L. McCally, Ph. D.	Principal Investigator
C. B. Bargeron, Ph. D.	co - Principal Investigator
S. O'Neal	Group Secretary

Appendix 2

```
C   PROGRAM CALCULATES TEMPERATURE-TIME HISTORIES FOR RADIATION
C   INCIDENT ON A SEMI-INFINITE ABSORBING SLAB
C  RADIATION CAN BE EITHER CW OR SEQUENCES OF PULSES
C  RADIATION AND CONVECTIVE HEAT TRANSFER ARE IGNORED
C  PROGRAM ADAPTED BY R. MCCALLY (FEBRUARY 14-MARCH 18 1996) FROM
C  MAINFRAME VERSION  WRITTEN BY S. FAVIN
C
C   S0    = IRRADIANCE (W/(CM*CM))
C   KAPPA = THERMAL CONDUCTIVITY (CAL/(CM*CM*DEGC))
C   R     = RADIAL DIST FROM BEAM AXIS (CM)
C   Z     = DEPTH (CM)
C   RE    = 1/E BEAM RADIUS (CM)
C   NPTS  = NUMBER OF CALC POINTS
C   TAU   = PULSE DURATION (SEC)
C   C     = HEAT CAPACITY (CAL/(GM*DEGC))
C   GAM   = INVERSE ABSORBTION LENGTH (1/CM)
C   DELT  = 1/PRF (SEC)  --- DELT MUST BE >= TAU
C   NP    = NUMBER OF PULSES
C   ND    = NUMBER OF INTERVALS CALCULATED DURING EACH PULSE
C   NRUNS = NUMBER OF SETS OF INPUT DATA
C
C   IRULE  - Choice of quadrature rule in DQDAG. (Input)
C          A Gauss-Kronrod rule is used with
C              7 - 15 points if IRULE = 1
C             10 - 21 points if IRULE = 2
C             15 - 31 points if IRULE = 3
C             20 - 41 points if IRULE = 4
C             25 - 51 points if IRULE = 5
C             30 - 61 points if IRULE = 6
C          IRULE = 2 is recommended for most functions.
C          If the function has a peak singularity use IRULE = 1.
C          If the function is oscillatory use IRULE = 6.
C
      PROGRAM IRTEMP
C
      IMPLICIT REAL*8(A-H,O-Z)
      REAL*8 KAPPA
      COMMON   ZO,ONE,TWO,TEN,HUN,SPI,W,ZA,GTA,AZ,E2,R2,  XO, TEGZ, G2FA
      DIMENSION TIME(8001),TEMP(8001),TEMPN(8001)
      DIMENSION IP(1000)
      CHARACTER*1 TAB
      EXTERNAL FF
C
      INN = 7           ! DEFINES INPUT LOGICAL UNIT
      IOUT = 8          ! DEFINES OUTPUT LOGICAL UNIT FOR FINAL DATA FILE
      ISCREEN = 6       ! DEFINES LOGICAL UNIT FOR OUTPUT TO SCREEN
      ICOUNT = 0        !INITIALIZE COUNTER FOR TIMES INPUT FILE IS ACCESSED
C
C   DEFINE CONSTANTS
      ZO = 0.0D0
      ONE = 1.0D0
      TWO = 2.0D0
      TEN = 10.0D0
      HUN = 100.0D0
```

```
      PI = 4.0D0 * DATAN( ONE )
      SPI = DSQRT( PI )
      TAB = CHAR(9)     ! TAB IS ASC 9
C
C   OPEN I/O FILES
      OPEN (UNIT=INN, FILE ='IRINPUT', STATUS='OLD',ACCESS='SEQUENTIAL', BLANK='NULL')
      OPEN (UNIT=IOUT, FILE ='IROUT', STATUS='UNKNOWN',ACCESS='SEQUENTIAL')
C
 1000 CONTINUE
C
C   GET INPUT DATA
      CALL INPUT(S0,KAPPA,R,Z,RE,NPTS,TAU,C,GAM,DELT,NP,ND,RHO,NRUNS,ICOUNT,INN,
     1IOUT,ISCREEN,AERR,RERR,IRULE)
C
      A2 = RHO*C/(4.0D0*KAPPA)
      TSIG = RE*RE
      R2 = R*R
      FRONT = S0*GAM/(8.36D0*RHO*C)
      ZA = Z**2 * A2
      AZ = DSQRT( ZA )
      TA = TWO * DSQRT( A2 )
      GTA = GAM/TA
      XO = TWO*A2*Z/GAM
      TEGZ = TWO * DEXP(-GAM*Z)
      G2FA = GAM**2 / (4.D0*A2)
      W = A2 * TSIG
C
C   CALCULATE TIME POINTS
      TIME(1) = ZO
      DO 30 I=1,ND
      TIME(I+1) = I*TAU/ND
   30 CONTINUE
      ND1 = ND + 1
      N2 = 2*ND
C   FOR SINGLE PULSES THIS LOOP GENERATES ND TIME POINTS BETWEEN TAU AND DELT
C     IF NPTS <2*ND IT GENERATES NPTS-ND POINTS WITH SPACING (DELT-TAU)/ND
      DO 32 I=ND1,N2
      TIME(I+1) = TAU + (I-ND)*(DELT - TAU)/ND
   32 CONTINUE
      ND2 = N2 + 1
C   FOR SINGLE PULSES THIS LOOP GENERATES NPTS-2*ND TIME POINTS AFTER DELT (SPACI
C     SAME AS DURING PULSE)
      DO 36 I=ND2,NPTS              ! DOES NOT EXECUTE IF NPTS<2*ND+1
        DO 34 J=1,NP
        K = J*N2
        IF(I .LE. K) GO TO 34
        TIME(I+1) = J*DELT + TIME(I+1-K)
   34   CONTINUE
   36 CONTINUE
      TEMP(1) = ZO
      WRITE(ISCREEN,4)
      WRITE(IOUT,5)TAB,TAB,TAB
C
C   BEGIN TEMPERATURE CALCULATION
      DO 100 I=2,NPTS
      TL = TIME(1)
      IF(TIME(I)-TAU .GT. TL) TL=TIME(I)-TAU
      TU = TIME(I)
```

```
      CALL DQDAG (FF, TL, TU, AERR, RERR, IRULE, PSI, ERREST)
      TEMP(I) = FRONT * PSI
      WRITE(ISCREEN,6) I,PSI,TIME(I),TEMP(I),ERREST
      WRITE(IOUT,7) I,TAB,PSI,TAB,TIME(I),TAB,TEMP(I),TAB,ERREST
  100 CONTINUE
C
C   HANDLE MULTIPLE PULSES
      IF(NP.EQ.1) GO TO 400
      IP(1)=1
      DO 50 J=2,NP
      IP(J) = (J-1) * ND * 2
   50 CONTINUE
      DO 300 I=1,NPTS
      TEMPN(I) = TEMP(I)
      IF(TIME(I) .LT. DELT) GO TO 300
        DO 200 J=2,NP
        IF(I .LE. IP(J)) GO TO 200
        L = I - IP(J)
        TEMPN(I) = TEMPN(I) + TEMP(L)
  200   CONTINUE
  300 CONTINUE
      GO TO 375
  350 DO 375 I=1,NPTS
      TEMPN(I) = TEMP(I)
  375 CONTINUE
C
C   WRITE TO FINAL DATA FILE (ONLY IF MULTIPLE PULSES)
      WRITE(IOUT,380)TAB,TAB            ! WRITE HEADER FOR RESULTS
      DO 400 I=1,NPTS
      WRITE(IOUT,390) I,TAB,TIME(I),TAB,TEMPN(I)
  400 CONTINUE
      IF (ICOUNT .LT. NRUNS) GO TO 1000
   99 STOP
C   3 FORMAT(' A2 = ',1PE14.5,' TSIG = ',1PE14.5,' R2 = ',1PE14.5,' FRONT = ',1PE14.5)
    4 FORMAT(T3,'I',T11,'PSI',T25,'TIME',T36,'TEMPERATURE',T52,'ERROR')
    5 FORMAT('I',A1,'PSI',A1,'TIME',A1,'TEMPERATURE',A1,'ERROR')
    6 FORMAT(I5,1PG14.6,1PG14.6,1PG14.6,1PG14.6)
    7 FORMAT(I5,A1,1PG14.7,A1,1PG14.7,A1,1PG14.7,A1,1PG14.7)
  380 FORMAT('I',A1,'TIME',A1,'TEMPERATURE')
  390 FORMAT(I5,A1,1PE14.8,A1,1PE14.8)
      END
C
C
      FUNCTION  FF ( X )
C    THIS DESCRIBES THE INTEGRAND
      IMPLICIT REAL*8(A-Z)
      COMMON   ZO,ONE,TWO,TEN,HUN,SPI,W,ZA,GTA,AZ,E2,R2,  XO, TEGZ, G2FA
C
      IF(X .EQ. ZO) GO TO 50
C
      X2 = DSQRT( X )
      XW = ONE + X/W
      EE = -R2/XW
      E1 = ZO
      IF(DABS(EE) .LE. HUN) E1 = DEXP( EE )
C
      E2 = -ZA/X
C
```

```
      C1 = GTA * X2
      C2 = AZ/X2
      ARG1 = C1 + C2
      ARG2 = C1 - C2
      H1 = HFUN( ARG1 )
      H2 = HFUN( ARG2 )
C
      IF(X .GT. XO) GO TO 10
C...    FOR X LESS THEN XO AND NOT ZERO     6/2/80    THE REVISION
      FO = E1/XW
      G1 = TEGZ * DEXP(G2FA*X)
      G2=ZO
      IF(DABS(E2) .GT. HUN) GO TO 30
        H1 = HFUN( DABS(ARG1) )
        H2 = HFUN( DABS(ARG2) )
      G2 = (H1-H2)
C
   30 FF = FO*(G1 + G2)
      RETURN
C
   10 CONTINUE
      FF = E1 * (H1 + H2) / XW
      RETURN
C...    FOR X= 0 ONLY
   50 CONTINUE
      FF = TEGZ * DEXP(-R2)
      RETURN
      END
C
C
      FUNCTION HFUN ( ARG )
      IMPLICIT REAL*8(A-Z)
      COMMON  ZO,ONE,TWO,TEN,HUN,SPI,W,ZA,GTA,AZ,E2,R2,  XO, TEGZ, G2FA
      DATA HALF,ONEH / 0.5D0, 1.50D0/
C
      Y = DABS( ARG )
      Y2 = Y*Y
      HFUN = ZO
      BB = Y2 + E2
      IF(ARG .GE. -13.0D0) GO TO 10
        B1=ZO
        IF(DABS(BB) .LE. 174.0D0) B1 = TWO * DEXP( BB )
        B2 = ZO
        IF(DABS(E2) .LT. 174.0D0)  B2 = DEXP(E2) /
     *   (SPI*(Y+HALF/(Y+ONE/(Y+ONEH/(Y+TWO/Y)))) )
        HFUN = B1 - B2
        RETURN
   10 CONTINUE
      IF(ARG .GE. ZO) GO TO 20
      IF(DABS(BB) .LT. 174.0D0) HFUN = DEXP(BB)*(TWO-DERFC(Y))
      RETURN
   20 CONTINUE
      IF(ARG .GT. 13.0) GO TO 30
      IF(DABS(BB) .LT. 174.0D0) HFUN = DEXP(BB)*DERFC(ARG)
      RETURN
   30 CONTINUE
      IF(DABS(E2) .GT. 174.0D0) GO TO 40
      Z = ARG
```

```
      HFUN = SPI*(Z+HALF/(Z+ONE/(Z+ONEH/(Z+TWO/Z))))
      IF(HFUN .NE. ZO) HFUN = DEXP(E2)/HFUN
   40 RETURN
      END
C
C
      FUNCTION DERFC(X)
C
C  RETURNS THE COMPLIMENTARY ERROR FUNCTION
c
c  checks with Mathematica to 15 significant figures
c    in range (.001 <= x <= 4.0) (Maximum printout from Mathematica
c     and maximum range checked  3/18/96 RLM)
c
      implicit real*8 (a-h,o-z)
      DATA Z0,HALF,ONE/0.0D0,0.5D0,1.0D0/
       IF(X.LT.z0)THEN
        DERFC=ONE+GAMMP(half,X**2)
       ELSE
        DERFC=GAMMQ(half,X**2)
       ENDIF
       RETURN
       END
c
      FUNCTION GAMMP(A,X)
      implicit real*8 (a-h,o-z)
      DATA Z0,HALF,ONE/0.0D0,0.5D0,1.0D0/
       IF(X.LT.z0.OR.A.LE.z0)PAUSE
       IF(X.LT.A+one)THEN
        CALL GSER(GAMSER,A,X,GLN)
        GAMMP=GAMSER
       ELSE
        CALL GCF(GAMMCF,A,X,GLN)
        GAMMP=one-GAMMCF
       END IF
       RETURN
       END
c
       FUNCTION GAMMQ(A,X)
       implicit real*8 (a-h,o-z)
       DATA Z0,HALF,ONE/0.0D0,0.5D0,1.0D0/
       IF(X.LT.Z0.OR.A.LE.Z0)PAUSE
       IF(X.LT.A+ONE)THEN
        CALL GSER(GAMSER,A,X,GLN)
        GAMMQ=ONE-GAMSER
       ELSE
        CALL GCF(GAMMCF,A,X,GLN)
        GAMMQ=GAMMCF
       ENDIF
       RETURN
       END

c
      SUBROUTINE GSER(GAMSER,A,X,GLN)
      implicit real*8 (a-h,o-z)
      DATA Z0,HALF,ONE/0.0D0,0.5D0,1.0D0/
       PARAMETER (ITMAX=400,EPS=10D-17)
       gln = 0.5723649429247001d0            ! ln(sqrt(pi)) = gamma(1/2)
```

```
      IF(X.LE.z0)THEN
       IF(X.LT.z0)PAUSE
       GAMSER=z0
       RETURN
      END IF
      AP=A
      SUM=one/A
      DEL=SUM
      DO 11 N=1,ITMAX
       AP=AP+one
       DEL=DEL*X/AP
       SUM=SUM+DEL
       IF(dABS(DEL).LT.dABS(SUM)*EPS)GO TO 1
11    CONTINUE
      PAUSE 'A too large, ITMAX too small'
1     GAMSER=SUM*dEXP(-X+A*dLOG(X)-GLN)
      RETURN
      END
c
      SUBROUTINE GCF(GAMMCF,A,X,GLN)
      implicit real*8 (a-h,o-z)
      DATA Z0,HALF,ONE/0.0D0,0.5D0,1.0D0/
      PARAMETER (ITMAX=400,EPS=10d-17)
      gln = 0.5723649429247001d0           ! ln(sqrt(pi)) = gamma(1/2)
      GOLD=z0
      a0=one
      A1=X
      B0=z0
      B1=one
      FAC=one
      DO 11 N=1,ITMAX
       AN=dFLOAT(N)
       ANA=AN-A
       A0=(A1+A0*ANA)*FAC
       B0=(B1+B0*ANA)*FAC
       ANF=AN*FAC
       A1=X*A0+ANF*A1
       B1=X*B0+ANF*B1
       IF(A1.NE.z0)THEN
        FAC=one/A1
        G=B1*FAC
        IF(DABS((G-GOLD)/G).LT.EPS)GO TO 1
        GOLD=G
       ENDIF
11    CONTINUE
      PAUSE 'A too large, ITMAX too small'
1     GAMMCF=dEXP(-X+A*dLOG(X)-GLN)*G
      RETURN
      END
C
C-----------------------------------------------------------------
      SUBROUTINE INPUT(S0,KAPPA,R,Z,RE,NPTS,TAU,C,GAM,DELT,NP,ND,RHO,NRUNS,
     1ICOUNT,INN,IOUT,ISCREEN,AERR,RERR,IRULE)
C-----------------------------------------------------------------
      IMPLICIT REAL*8(A-H,O-Z)
      REAL*8 KAPPA
C     INTEGER*4 NPTS,NP,ND,NRUNS,ICOUNT,INN,IOUT,ISCREEN,IRULE,I
      CHARACTER*9 DAY
```

```
      CHARACTER*11 AD1
      CHARACTER*30 AIN2
C
C PURPOSE:  READ INPUT FILE IRINPUT AND WRITE PARAMETERS.
C
C INPUT:    INN,IOUT,ISCREEN
c
C
C OUTPUT:   S0,KAPPA,R,Z,RE,NPTS,TAU,C,GAM,DELT,NP,ND,
C         RHO,NRUNS,ICOUNT,AERR,RERR,IRULE.
C
      ICOUNT=ICOUNT+1                         ! INCREMENT FILE ACCESS COUNTER
C     READ FILE INN.
C
      READ(INN,'(A30)',END=99,IOSTAT=I)AIN2         ! READ HEADER
      READ(INN,'(A30)',END=99,IOSTAT=I)AIN2         ! READ ---
      READ(INN,'(A11)',END=99,IOSTAT=I)AD1          ! READ123 ETC
      READ(INN,'(A11,I5)',END=99,IOSTAT=I)AD1,NRUNS
      READ(INN,'(A11,1PG14.6)',END=99,IOSTAT=I)AD1,S0
      READ(INN,'(A11,1PG14.6)',END=99,IOSTAT=I)AD1,TAU
      READ(INN,'(A11,F14.9)',END=99,IOSTAT=I)AD1,RE
      READ(INN,'(A11,F14.9)',END=99,IOSTAT=I)AD1,Z
      READ(INN,'(A11,F14.9)',END=99,IOSTAT=I)AD1,R
      READ(INN,'(A11,I5)',END=99,IOSTAT=I)AD1,NP
      READ(INN,'(A11,1PG14.6)',END=99,IOSTAT=I)AD1,DELT
      READ(INN,'(A11,I5)',END=99,IOSTAT=I)AD1,ND
      READ(INN,'(A11,I5)',END=99,IOSTAT=I)AD1,NPTS
      READ(INN,'(A11,F14.9)',END=99,IOSTAT=I)AD1,GAM
      READ(INN,'(A11,F14.9)',END=99,IOSTAT=I)AD1,C
      READ(INN,'(A11,F14.9)',END=99,IOSTAT=I)AD1,KAPPA
      READ(INN,'(A11,F14.9)',END=99,IOSTAT=I)AD1,RHO
C.....INTEGRATION PARAMETERS:
      READ(INN,'(A11,F14.9)',END=99,IOSTAT=I)AD1,AERR
      READ(INN,'(A11,1PD14.9)',END=99,IOSTAT=I)AD1,RERR
      READ(INN,'(A11,I5)',END=99,IOSTAT=I)AD1,IRULE
C
C WRITE INPUT TO FILE IROUT ( DISK DATA FILE)
C
      WRITE(IOUT,100)
      WRITE(IOUT,105)
      CALL DATE(DAY)
      WRITE(IOUT,110)DAY
      AIN2 = ' INPUT PARAMETERS'
      WRITE(IOUT,110)AIN2
      WRITE(IOUT,150)NRUNS
      WRITE(IOUT,151)S0
      WRITE(IOUT,152)TAU
      WRITE(IOUT,153)RE
      WRITE(IOUT,154)Z
      WRITE(IOUT,166)R
      WRITE(IOUT,155)NP
      WRITE(IOUT,156)DELT
      WRITE(IOUT,157)ND
      WRITE(IOUT,158)NPTS
      WRITE(IOUT,159)GAM
      WRITE(IOUT,160)C
      WRITE(IOUT,161)KAPPA
      WRITE(IOUT,162)RHO
```

```
      AIN2 = ' INTEGRATION PARAMETERS:  '
      WRITE(IOUT,110)AIN2
      WRITE(IOUT,163)IRULE
      WRITE(IOUT,164)AERR
      WRITE(IOUT,165)RERR
C
C WRITE INPUT TO SCREEN
C
      WRITE(ISCREEN,100)
      WRITE(ISCREEN,110)DAY
      AIN2 = ' INPUT PARAMETERS'
      WRITE(ISCREEN,110)AIN2
      WRITE(ISCREEN,150)NRUNS
      WRITE(ISCREEN,151)S0
      WRITE(ISCREEN,152)TAU
      WRITE(ISCREEN,153)RE
      WRITE(ISCREEN,154)Z
      WRITE(ISCREEN,166)R
      WRITE(ISCREEN,155)NP
      WRITE(ISCREEN,156)DELT
      WRITE(ISCREEN,157)ND
      WRITE(ISCREEN,158)NPTS
      WRITE(ISCREEN,159)GAM
      WRITE(ISCREEN,160)C
      WRITE(ISCREEN,161)KAPPA
      WRITE(ISCREEN,162)RHO
      AIN2 = ' INTEGRATION PARAMETER:  '
      WRITE(ISCREEN,110)AIN2
      WRITE(ISCREEN,163)IRULE
      WRITE(ISCREEN,164)AERR
      WRITE(ISCREEN,165)RERR
99    CONTINUE
C
C FINAL WRITE STATEMENTS
C
      WRITE(IOUT,120)
      WRITE(ISCREEN,120)
      RETURN
C
100   FORMAT(/' ---WE ARE IN IRINPUT --- '/)
105   FORMAT(/' --- FILE IROUT--- '/)
110   FORMAT(A35)
120   FORMAT(/' ---LEAVING IRINPUT--- '/)
130   FORMAT(' ... ')
150   FORMAT(' NRUNS   =',I5)
151   FORMAT(' SO      =',1PG14.5,' WATTS/CM**2')
152   FORMAT(' TAU     =',1PG14.5,' SEC')
153   FORMAT(' RE      =',F14.5,' CM')
154   FORMAT(' Z       =',F14.5,' CM')
155   FORMAT(' NP      =',I5,'          PULSES')
156   FORMAT(' DELT    =',1PG14.5,' SEC')
157   FORMAT(' ND      =',I5,'          INTERVALS/PULSE')
158   FORMAT(' NPTS    =',I5)
159   FORMAT(' GAM     =',F14.5,' 1/CM')
160   FORMAT(' C       =',F14.5,' CAL/(GM*DEGC)')
161   FORMAT(' KAPPA   =',F14.5,' CAL/(CM**2*DEGC)')
162   FORMAT(' RHO     =',F14.5,' GM/CM**2')
163   FORMAT(' IRULE   =',I5)
```

```
164  FORMAT(' AERR   =',F14.5)
165  FORMAT(' RERR   =',1PD14.5)
166  FORMAT(' R      =',F14.5,' CM')
   END
C
C-----------------------------------------------------------------
C IMSL Name:  QDAG/DQDAG (Single/Double precision version)
C
C Computer:  PCDSMS/DOUBLE
C
C Revised:   January 29, 1985
C
C Purpose:   Integrate a function using a globally adaptive
C            scheme based on Gauss-Kronrod rules.
C
C Usage:     CALL QDAG (F, A, B, ERRABS, ERRREL, IRULE, RESULT,
C                 ERREST)
C
C Arguments:
C   F      - User-supplied FUNCTION to be integrated.  The form is
C            F(X), where
C            X      - Independent variable. (Input)
C            F      - The function value. (Output)
C            F must be declared EXTERNAL in the calling program.
C   A      - Lower limit of integration. (Input)
C   B      - Upper limit of integration. (Input)
C   ERRABS - Absolute accuracy desired. (Input)
C   ERRREL - Relative accuracy desired. (Input)
C   IRULE  - Choice of quadrature rule. (Input)
C            A Gauss-Kronrod rule is used with
C                 7 - 15 points if IRULE = 1
C                10 - 21 points if IRULE = 2
C                15 - 31 points if IRULE = 3
C                20 - 41 points if IRULE = 4
C                25 - 51 points if IRULE = 5
C                30 - 61 points if IRULE = 6
C            IRULE = 2 is recommended for most functions.
C            If the function has a peak singularity use IRULE = 1.
C            If the function is oscillatory use IRULE = 6.
C   RESULT - Estimate of the integral from A to B of F. (Output)
C   ERREST - Estimate of the absolute value of the error. (Output)
C
C Remarks:
C 1. Automatic workspace usage is
C            QDAG    2500 units, or
C            DQDAG   4500 units.
C   Workspace may be explicitly provided, if desired, by use of
C   Q2AG/DQ2AG.  The reference is
C            CALL Q2AG (F, A, B, ERRABS, ERRREL, IRULE, RESULT,
C                    ERREST, MAXSUB, NEVAL, NSUBIN, ALIST, BLIST,
C                    RLIST, ELIST, IORD)
C   The additional arguments are as follows:
C   MAXSUB - Number of subintervals allowed. (Input)
C            A value of 500 is used by QDAG.
C   NEVAL  - Number of evaluations of F. (Output)
C   NSUBIN - Number of subintervals generated. (Output)
C   ALIST  - Array of length MAXSUB containing a list of the NSUBIN
C            left endpoints. (Output)
```

```
C    BLIST  - Array of length MAXSUB containing a list of the NSUBIN
C             right endpoints.  (Output)
C    RLIST  - Array of length MAXSUB containing approximations to
C             the NSUBIN integrals over the intervals defined by ALIST,
C             BLIST.  (Output)
C    ELIST  - Array of length MAXSUB containing the error estimates of
C             the NSUBIN values in RLIST.  (Output)
C    IORD   - Array of length MAXSUB.  (Output)
C             Let K be
C                NSUBIN          if NSUBIN .LE. (MAXSUB/2+2)
C                MAXSUB+1-NSUBIN otherwise.
C             The first K locations contain pointers to the error
C             estimates over the corresponding subintervals, such that
C             ELIST(IORD(1)), ..., ELIST(IORD(K)) form a decreasing
C             sequence.
C
C  2. Informational errors
C     Type Code
C       4   1  The maximum number of subintervals allowed has been
C              reached.
C       3   2  Roundoff error, preventing the requested tolerance from
C              being achieved, has been detected.
C       3   3  A degradation in precision has been detected.
C
C  3. If EXACT is the exact value, QDAG attempts to find RESULT
C     such that ABS(EXACT-RESULT) .LE. MAX(ERRABS,ERRREL*ABS(EXACT)).
C     To specify only a relative error, set ERRABS to zero.  Similarly,
C     to specify only an absolute error, set ERRREL to zero.
C
C  GAMS:      H2a1a1
C
C  Chapter:   MATH/LIBRARY Integration and Differentiation
C
C  Copyright:  1985 by IMSL, Inc.  All Rights Reserved.
C
C  Warranty:  IMSL warrants only that IMSL testing has been applied
C             to this code.  No other warranty, expressed or implied,
C             is applicable.
C
C-----------------------------------------------------------------------
```